Applied Thermal Engineering 144 (2018) 614–627

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Energy-exergy analysis and energy efficiency improvement of coal-fired industrial boilers based on thermal test data

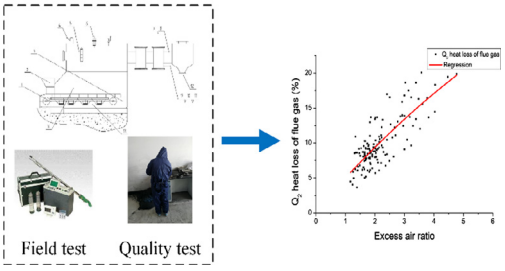
Qi Zhang[a,*], Henan Yi[a], Zaihai Yu[b], Jintong Gao[a], Xiaozhuang Wang[a], Heyong Lin[c], Bo Shen[d]

[a] State Environmental Protection Key Laboratory of Eco-Industry, Northeastern University, Shenyang 110819, Liaoning, PR China
[b] Energy Saving Center of Boilers, Liaoning Academy of Safety Science, Shenyang 110004, Liaoning, PR China
[c] Yingkou Institute of Boiler and Pressure Vessel Inspection, Yingkou 115000, Liaoning, PR China
[d] Energy Analysis and Environmental Impacts Division, Lawrence Berkey National Laboratory, Berkeley, CA 94720, USA

HIGHLIGHTS

- Detailed energy and exergy analysis of tested industrial boilers are performed.
- Influence factors of energy efficiency of coal-fired boilers are discussed.
- Carbon dioxide emissions of industrial coal-fired boilers are calculated.
- Improvement potential for energy conservation and pollution reducing is revealed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Energy analysis
Exergy analysis
Carbon emission
Industrial boilers

ABSTRACT

Energy conservation and emission reduction in coal-fired boilers are significant to mitigate climate change and alleviate environmental pollution. In this study, the potential for efficiency promotion is assessed by understanding the factors affecting boiler performance. The results are based on thermal tests of 141 coal-fired industrial boilers in Liaoning province, China. Additionally, an exergy analysis model suitable for coal-fired industrial boilers is proposed under the framework of the first and second laws of thermodynamics to improve the operation of boilers. The energy and exergy efficiencies as well as CO_2 emissions have been discussed as well. The results indicate that the heat loss of flue gas and unburnt carbon represent the main heat losses. Exergy loss is dominated by destruction due to irreversibility in coal combustion and heat transfer. Average energy efficiency and CO_2 emission of 141 boilers were estimated to be 76.08% and 147.13 kg-CO_2/GJ, respectively. Exergy efficiencies of typical samples were estimated at about 12.88% for hot water boiler and 27.97% for steam boiler. Raising the efficiencies of 141 boilers to the target level proposed in the standard will lead to a decrease of coal consumption by 155 kt, emission reduction of 341 kt for CO_2, 3.72 kt for SO_2, and 3.48 kt for NO_x per year.

1. Introduction

Recently, the impact of energy consumption and CO_2 emissions on climate change and energy resource depletion has received global attention. In 2017, the International Energy Agency (IEA) released a report, with special focus on China, to examine the influence of Chinese policies towards reshaping the global outlook for various fuels and technologies [1]. In China, boilers are the major energy consumption

* Corresponding author.
E-mail address: zhangqi@mail.neu.edu.cn (Q. Zhang).

https://doi.org/10.1016/j.applthermaleng.2018.08.069
Received 18 February 2018; Received in revised form 23 July 2018; Accepted 19 August 2018
Available online 24 August 2018
1359-4311/ © 2018 Elsevier Ltd. All rights reserved.

Nomenclature

A	ash content, %
B	coal consumption, kg/h
C	carbon content,%
C'	mass flow rate of unburnt carbon, kg/h
E	energy, GJ/h
Ex	exergy, GJ/h
ex	specific exergy, GJ/kg
h	specific enthalpy, GJ/kg
I_i	exergy destruction of irreversibility, GJ/h
LHV	lower heat value, GJ/kg
M	moisture, %
m	mass flow rate, kg/h
P	pressure, kPa
Q	boiler capacity, MW
Q_i	energy loss, %
R	universal gas constant
s	specific entropy, GJ/kg·K
T	temperature, K
V	volume of gas, m^3

Greek letters

γ	vaporization sensible heat of water, GJ/kg
η	efficiency, %
ω	humidity, %

Chemical symbols

C	carbon
CO	carbon monoxide
CO_2	carbon dioxide
H	hydrogen
N	nitrogen
NO_x	nitrogen oxides
O	oxygen
S	sulfur
SO_2	sulfur dioxide

Sub-and-superscripts

ad	adiabatic
ar	as received
ch	cinder heat
cu	unburnt carbon
d	direct balance
fa	fly ash
fg	flue gas
hp	hot product
id	indirect balance
in	in
lc	leakage coal
out	out
sl	slag
su	boiler surface
wi	water in
wo	water out

equipment and one of the key sources of greenhouse gas emissions as well as local pollution [2,3]. As a result, it is crucial to develop the coal-fired boilers with higher-efficiency and lower-emission [4,5]. According to the investigation conducted by the Ministry of Industry and Information Technology and General Administration of Quality Supervision, Inspection and Quarantine of China, towards the end of 2016, there were about 534,400 in-use boilers in China [6], of these, about 427,000 boilers consume coal as fuel, at 1.78 million steam tons, accounted for 80% of the total boiler capacity [7]. These boilers consume about 1.1 billion tons of coal annually, accounting for 25% of the national total coal consumption and have a small average capacity of 2.7 MW [8], which produce approximately 1.3 gigatons (Gt) of carbon dioxide (CO_2) annually [9]. The reason is the main fuel for industrial boilers in China is raw coal. Moreover, as a result of the general lack or failure of desulfurization, denitration, and dust removal equipment, these boilers are also the main sources of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and soot and account for 27%, 9%, and 33% of total emissions in China, respectively [10]. Compared to the utility boiler, the single capacity of industrial boiler is small (less than 200 MW) but the quantity is large. For dealing with the environmental crisis engendered by coal-fired industrial boilers, the Chinese government has issued a series of policies related to industrial boilers, such as a national Boiler Action Plan for reducing energy use and controlling pollution resulting from coal-fired industrial boilers [2,3].

District heating system is widespread in the colder regions of China and most heating systems employ boilers to produce hot water or steam. It is one of the main applications of coal-fired industrial boilers. Additionally, the boilers always operate at an inferior level with an efficiency about 65% when employed in heating systems or as part of manufacturing industries [11]. Overall, the operation efficiency is about 15% lower than the international advanced performance level [12]. As a representative cold region in China, Liaoning province is not only a large coal producer but also a large coal consumer. At present, Liaoning province, with a total of about 33,000 industrial boilers, has an annual coal consumption of about 30 million tons and produces 55 million tons of CO_2, 400 thousand tons of SO_2, 400 thousand tons of NO_x, 500 thousand tons of soot, and 5 million tons of solid waste. Therefore, the energy savings and emission reduction of industrial boilers are significant for national energy structure transforms and environmental protection.

Conventionally, the first law of thermodynamics is used to measure the efficiency of energy utilization by a boiler in actual operation However, it is unable to account for the quality aspect of energy [13]. Exergy analysis is an effective tool in the regard of analysis of thermodynamic systems [2]. Some research on energy and exergy analyses for the utility boiler and other components of a power plant has been previously conducted. Aljundi et al. presented a detailed break-up of energy and exergy losses to estimate the system performance of a steam power plant in Jordan with a component-wise analysis model [14]. The energy efficiency of entire system was 26% approximately, the maximum energy loss was found in the condenser, followed by energy losses in the boiler, the percentages of the two losses were 66% and 6% of the input energy, respectively, and it was less than 2% for all other components. On the other hand, the exergy efficiency of the overall power cycle was calculated as 25%, the major loss was found in the boiler where 77% of the fuel exergy input to the cycle was destroyed. Uysal et al. carried out the exergy analyses of a power plant applied coal as fuel in Turkey, the exergy efficiency of entire cycle was found as 39.89%, the most irreversible process occurs in the steam boiler cause the maximum exergy destruction as 45.96% of input exergy [15]. Pattanayak and Ayyagari studied the energy and exergy analysis in a 400 MW coal-fired boiler in a power plant [16]. The energy and exergy efficiencies of the sample boiler were 85% and 41% respectively and more than 50% of total irreversibility was indicated in the boiler. Other

research [17] conducted the study of the boiler system using advanced exergy analysis which highlighted the destruction of exergy due to interaction among the components. This method is applicable to a power plant energy system due to the presence of a large number of subcomponents [18,19]. However, it is not suitable for an industrial boiler.

Different from utility boiler, the industrial boilers are more numerous and its types are also more complex. Saidur et al. analyzed the energy and exergy utilization in a steam industrial boiler [12]. The results indicated that the combustion chamber is the major contributor to exergy destruction followed by the heat exchanger of the boiler system. In their study, the energy and exergy efficiencies were found to be 72.46% and 24.89%, respectively. The exergy loss of flue gas accounted for 23% of the total losses while other exergy losses accounted for 52%. Meryem and Kemal performed energy and exergy analyses for natural gas fired boilers in a district heating system [2] and found the ratio of flue gas energy and exergy losses in the boilers to be 16.81% and 6.14%, respectively. Additionally, the energy and exergy efficiencies of the boilers were estimated to be 82% and 32.78%, respectively. Most of the previous exergy analyses of industrial boilers selected natural gas boilers as samples and the analysis models adopted were also only applicable to natural gas boilers. However, the energy structure of China is coal-based and a majority of industrial boilers use coal as fuel. Moreover, the flows of material in coal-fired industrial boilers are more complex than those in natural gas boilers, thus, the previous analysis methods are not suitable for coal-fired industrial boilers in China.

Furthermore, coal combustion is recognized as a significant anthropogenic source of atmospheric pollutants in China [20]. China's power industry contributes around 40% CO_2 emissions to the national total [21]. The CO_2 and contaminants emissions of boilers have been paid attention to by the academic community. Zeng and Fang et al. analyzed the mitigation of CO_2 emissions from industrial boilers in three typical colder industrial regions of China [10,22]. In their study, a method for calculating the CO_2 emissions from coal-fired industrial boiler was presented based on the data obtained from thermal tests. The average efficiency of the boilers was approximately 65%. The main causes of low efficiencies and high CO_2 emissions from industrial boilers were found to be high excess air and unburnt carbon in the slag and fly ash. However, the potential for energy conservation and contaminants emission reduction brought by the promotion of boiler efficiency were not mentioned in the research.

The analysis of industrial boiler based on multiple samples requires large volumes of actual thermal test data from diverse boilers. The results obtained from studying only one or two boilers do not have the universality of representing regional characteristics and are unable to provide reasonable proposals for other boilers to achieve the optimization of regional industrial boiler operations. In this study, for determining the status of coal-fired industrial boilers in the region, general investigation and thermal tests, including collection of basic data on energy utilization and CO_2 emissions of 141 coal-fired industrial boilers, were conducted for the district heating system in Liaoning province, which are in-use and more representative to evaluate the performance of industry boiler more clearly. Additionally, an exergy analysis model applicable for coal-fired industrial boiler was developed. The energy and exergy efficiencies, energy losses, exergy destruction, and CO_2 emissions for industrial boilers were subsequently calculated. Based on the results of the analyses, the proportion of energy and exergy losses of the boilers were expounded and the factors influencing boilers efficiencies were established. Moreover, boilers with different working media, capacities, and shortcomings in operation were selected for comparison. Then, the analysis of the potential of energy conservation and emission reduction due to efficiency promotion of 141 boilers was proposed. It is important to note that the efficiency improvement and reduced energy losses/exergy destruction of industrial boilers will play a significant role in energy savings and environmental pollution mitigation.

The remainder of this paper is organized as follows: Section 2 describes the methodology adopted in this study. Section 3 provides the data collection methods. The main results and discussions are presented in Sections 4 and 5. Section 6 concludes this paper.

2. Methodology

This section describes the methodology used to establish the balance of energy and exergy utilization for calculating the efficiencies and CO_2 emissions of coal-fired industrial boilers.

2.1. Energy analysis of industry boilers

According to the current standards stipulated by government [23,24], the efficiency of a coal-fired industrial boiler is deduced by applying both direct and indirect balance methods.

The basic energy balance of a coal-fired industrial boiler is as follows:

$$E_{in} = E_{out} + E_{loss} \tag{1}$$

The direct balance efficiency considered in the current standards is based on the following equations:

$$\eta_d = \frac{E_{out}}{E_{in}} \tag{2}$$

where E_{in} is the energy brought into the boiler system. When the air is not preheated, E_{in} can be calculated using the value of coal consumption (B) and the lower heating value of coal (LHV) as shown below:

$$E_{in} = E_{fuel} = B{\cdot}LHV \tag{3}$$

E_{out}, the energy transferred to water from hot-water boiler or a saturated-steam boiler can be represented as:

For hot-water boiler:

$$E_{out} = m_{feed-water}\,(h_{out} - h_{in}) \tag{4}$$

For saturated-steam boiler:

$$E_{out} = m_{steam}\left(h_{out} - h_{in} - \frac{\gamma\omega}{100}\right) \tag{5}$$

where $m_{feed\text{-}water}$ is the mass flow rate of feed water, m_{steam} is the mass flow rate of steam, h is the specific enthalpy of hot water or steam, γ is the vaporization sensible heat of water, and ω is the steam humidity.

The direct and indirect balance methods are both applied in the detailed test of industrial boiler performance. A simplified test of industrial boiler performance is recommended using the indirect balance method and the equation is as follows:

$$\eta_{id} = 1 - \frac{E_{loss}}{E_{in}} = 1 - \frac{(Q_2 + Q_3 + Q_4 + Q_5 + Q_6)}{B{\cdot}LHV} \tag{6}$$

In Eq. (6), Q_2 to Q_6 represent the five dominant energy losses in the daily operation of a coal-fired industrial boiler. The specific meanings and influencing factors of a coal-fired boiler are described in Fig. 1 and their influence on energy efficiency has been discussed in Section 5.1.

2.2. Exergy analysis model

Exergy is the maximum work potential of a system, a stream of matter, or a heat interaction with respect to a reference environment. The environment serves as a reservoir of thermal, mechanical, and chemical energies. The intensive properties of the environment do not significantly change as a result of the processes being considered and it experiences only internally reversible processes.

2.2.1. Analysis model of the boiler system

The exergy analysis models constructed for industrial boilers in previous studies [4,12] were applicable only to gas-fired boilers and

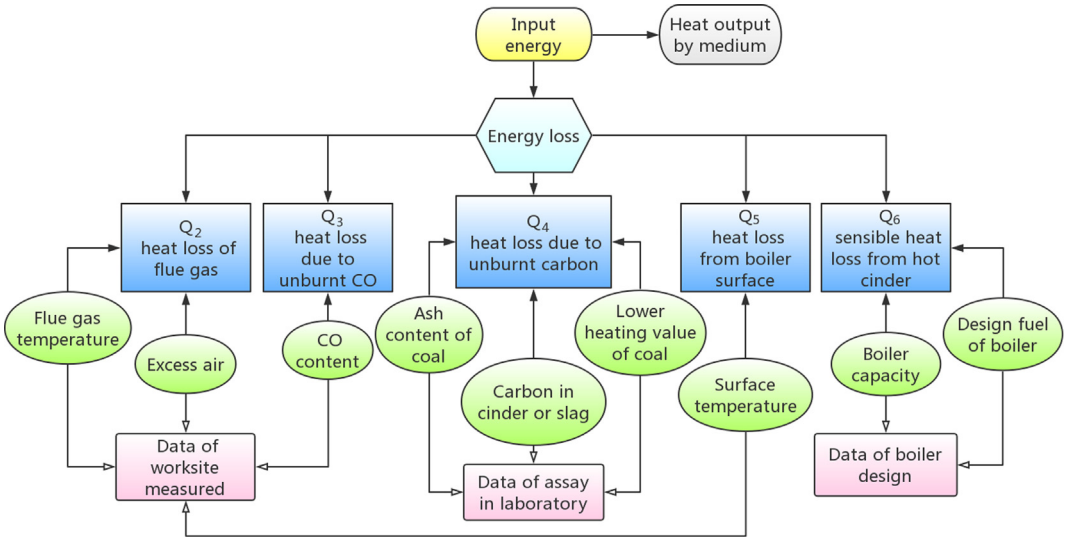

Input energy
Heat output by medium
Energy loss
Q2 heat loss of flue gas
Q3 heat loss due to unburnt CO
Q4 heat loss due to unburnt carbon
Q5 heat loss from boiler surface
Q6 sensible heat loss from hot cinder
Flue gas temperature
Excess air
CO content
Ash content of coal
Carbon in cinder or slag
Lower heating value of coal
Surface temperature
Boiler capacity
Design fuel of boiler
Data of worksite measured
Data of assay in laboratory
Data of boiler design

Fig. 1. Dominant energy losses and factors influencing a coal-fired boiler.

thus, a new exergy analysis model suitable for coal-fired boilers based on previous research is proposed. It should be noted that data from the detailed test of industrial boiler performance are a requirement for this exergy analysis model as shown in Fig. 2.

For estimating the boiler exergy consumption, the following assumptions are made:

- The temperature and pressure of the environmental state are assumed as $T_0 = 20\ ^\circ C$ and $P_0 = 1$ atm.
- The working condition of sample boilers is steady, the kinetic and potential energy changes of material flows are neglected.
- The boiler system is divided into two components, i.e., the combustion chamber and the heat exchanger and there is no exergy loss in the components except the mentioned flows.
- Reaction in the combustion chamber is an adiabatic complete combustion between fuel and dry air.
- Chemical exergy is considered only in the combustion process.
- The hot products (products of adiabatic combustion) and flue gas are assumed to be ideal gases.

The exergy balance equation of the entire coal-fired boiler is given as:

$$Ex_{in} = Ex_{out} + \sum Ex_{loss} + \sum I \tag{7}$$

where Ex_{in} is the exergy brought into the boiler system. When the air is not preheated, Ex_{in} can be calculated as the exergy of coal. Ex_{out} is the exergy of hot water or steam. ΣEx_{loss} is the total exergy loss of coal-fired boiler. ΣI is the total exergy destruction of irreversibility in the boiler.

The exergy efficiency of the boiler can be calculated with following equation:

$$\eta = \frac{Ex_{out}}{Ex_{in}} \tag{8}$$

According to the working process of the boiler, the total exergy loss or destruction is divided into four dominant streams. Moreover, the total exergy destruction of irreversibility is divided into I_1 (exergy destruction of combustion irreversibility) and I_2 (exergy destruction of heat transfer irreversibility).

The exergy values of streams mentioned in the model are calculated as follows:

$$Ex_{in} = Ex_{coal} + Ex_{air} \tag{9}$$

In the daily operation of a coal-fired industrial boiler, coal and air are supplied without preheating, thus, the Ex_{in} is equal to the chemical exergy of coal [11].

Due to variations in the type of the coals supplied to industrial boilers for calculating the chemical exergy of coals, the following equations can be used [25]:

For hard coals and anthracites:

$$Ex_{fuel} = \left[1.009 + \frac{1.031O_{ar} + 0.116M_{ar}}{100-(A_{ar} + M_{ar})}\right] \cdot LHV \tag{10}$$

For brown coals and peat:

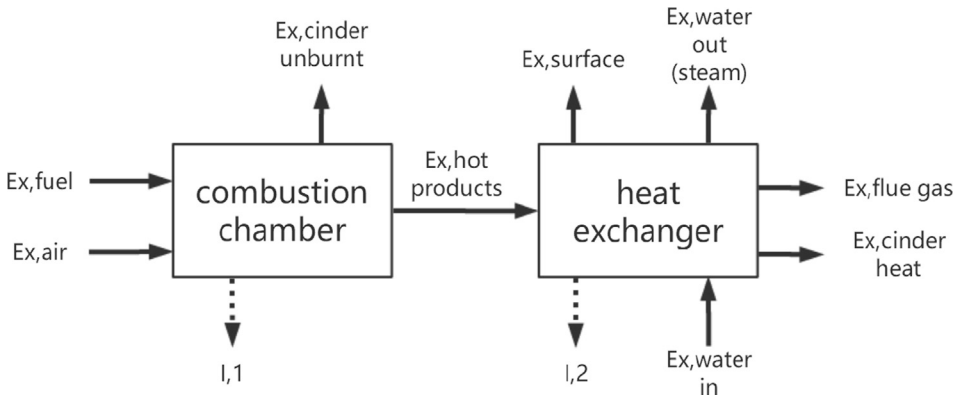


Fig. 2. Schematic diagram of the coal-fired boiler exergy analysis model.

$$Ex_{fuel} = \left[0.978 + \frac{0.267O_{ar} + 0.103M_{ar}}{100-(A_{ar} + M_{ar})}\right] \cdot LHV \quad (11)$$

In Eqs. (10) and (11), O_{ar}, A_{ar}, and M_{ar} are the oxygen content, ash content, and moisture of coal as received, respectively.

E_{out}, the utilized exergy of hot water or steam, can be calculated based on the exergies of feed water and hot water (steam) by the following equation:

For hot-water boiler:

$$Ex_{out} = Ex_{wo} - Ex_{wi} = m_{feed-water}[(h_{wo} - h_{wi}) - T_0(s_{wo} - s_{wi})] \quad (12)$$

For saturated-steam boiler:

$$Ex_{out} = Ex_{steam} - Ex_{wi} = m_{steam}[(h_{steam} - h_{wi}) - T_0(s_{steam} - s_{wi})] \quad (13)$$

For analyzing exergy utilization of the two components of the boiler system, the exergy balance equations have been shown below.

2.2.2. Analysis model for the combustion chamber

In the combustion chamber, the reaction is assumed to be insulated implying nearly zero heat dissipation to the environment. Thus, the exergy balance equation can be written as:

$$Ex_{fuel} + Ex_{air} = Ex_{hp} + Ex_{cu} + I_1 \quad (14)$$

Additionally, the temperatures of coal and combustion air are considered to be at environmental state, and thus, the exergy of combustion air is neglected.

Where Ex_{hp} is the exergy of hot product and it is calculated at environmental pressure as follows:

$$Ex_{hp} = BCp_{hp} \cdot V_{hp}\left[(T_{ad} - T_0) - T_0\left(\ln\frac{T_{ad}}{T_0}\right)\right] RT_0 \ln\left(\frac{P_{hp}}{P_0}\right) \quad (15)$$

C_p, h_p and V_{hp} denote the specific heat and theoretic volume of the hot product, respectively. T_{ad} is the adiabatic combustion temperature of coal. P_{hp} is the pressure of hot product. R is the universal gas constant The specific method of calculation can be found in [26].

Ex_{cu} is the chemical exergy of the unburnt carbon in cinders at environmental temperature. The exergy of sensible heat-loss due to hot cinders is analyzed in the heat exchanger component. The equations are expressed as:

$$Ex_{cu} = ex_{Cc}(C_{sl}m_{sl} + C_{lc}m_{lc} + C_{fa}m_{fa}) \quad (16)$$

where ex_{Cc} is the specific chemical exergy of carbon. The cinder of coal-fired boiler consists of three parts: slag, leakage coal, and fly ash. C and m are the contents of unburnt carbon and the rate of mass of stream, respectively.

As a result of combustion irreversibility in the combustion chamber, the exergy destruction I_1 is expressed as:

$$I_1 = Ex_{fuel} + Ex_{air} - (Ex_{hd} + Ex_{cu}) \quad (17)$$

2.2.3. Analysis model for the heat exchanger

In the heat exchanger, it is assumed that there is no chemical reaction in the component and the composition of flue gas is the same as hot products of combustion. Thus, the exergy balance equation can be written as:

$$Ex_{hp} + Ex_{wi} = Ex_{wo(steam)} + Ex_{fg} + Ex_{su} + Ex_{ch} + I_2 \quad (18)$$

Thus:

$$Ex_{out} = Ex_{wo(steam)} - Ex_{wi} \quad (19)$$

Eq. (18) can be rewritten as follow:

$$Ex_{hp} = Ex_{out} + Ex_{fg} + Ex_{ch} + Ex_{su} + I_2 \quad (20)$$

In Eq. (20), Ex_{fg} is the exergy of flue gas and it can be obtained by the methods used for estimation of Ex_{hp} as follow:

$$Ex_{fg} = BCp_{fg} \cdot V_{fg}\left[(T_{fg} - T_0) - T_0\left(\ln\frac{T_{fg}}{T_0}\right)\right] RT_0 \ln\left(\frac{P_{fg}}{P_0}\right) \quad (21)$$

T_{fg} is the temperature of flue gas measured at worksite, Cp_{fg} and V_{fg} denote the specific heat and theoretic volume of flue gas at that temperature, respectively.

Ex_{su} is the exergy of heat dissipation from the boiler's surface and it can be calculated by the following equation:

$$Ex_{su} = Q_5\left(1 - \frac{T_0}{T_{su}}\right) \quad (22)$$

In the equation, T_{su} is the temperature of the boiler's surface, Q_5 is heat loss from the surface (obtained by the indirect balance method of boiler performance test). Ex_{ch} is the exergy of sensible heat-loss due to hot cinders and the equation is shown as:

$$Ex_{ch} = Q_6\left(1 - \frac{T_0}{T_{hc}}\right) \quad (23)$$

In Eq. (23), T_{hc} is the temperature of hot cinders measured at the end of grate and Q_6 is the sensible heat loss of hot cinders. I_2 denotes the other irreversibility of the boiler emerging during the heat transfer into water. The exergy destruction is expressed as:

$$I_2 = Ex_{hp} - (Ex_{out} + Ex_{fg} + Ex_{ch} + Ex_{su}) \quad (24)$$

2.3. CO_2 emission analysis

CO_2 is the product of combustion of carbonaceous fuels, such as coal. Additionally, coal combustion emits the largest amount of CO_2 per unit of heat produced because of the highest C/H ratio in its chemical composition [7].

For calculation of CO_2 emissions of a coal-fired boiler, data for the mass flow rate of burnt carbon are needed. These data can be estimated from the content of unburnt carbon in cinder using the following equations [11].

The residual carbon in the slag, leakage coal, and fly ash can be estimated by the following equations:

$$C_{sl} = \frac{C'_{sl}}{80\%BA_{ar} + C'_{sl}} \quad (25)$$

$$C_{lc} = \frac{C'_{lc}}{15\%BA_{ar} + C'_{lc}} \quad (26)$$

$$C_{fa} = \frac{C'_{fa}}{5\%BA_{ar} + C'_{fa}} \quad (27)$$

where A_{ar} is the ash content of coal as received and C′ is the mass flow rate of unburnt carbon.

We can obtain C' by rewriting Eqs. (25)–(27) as:

$$C'_{sl} = \frac{80\%BA_{ar}C_{sl}}{1-C_{sl}} \quad (28)$$

$$C'_{lc} = \frac{15\%BA_{ar}C_{lc}}{1-C_{lc}} \quad (29)$$

$$C'_{fa} = \frac{5\%BA_{ar}C_{fa}}{1-C_{fa}} \quad (30)$$

Thus, the mass flow rate of burnt carbon is given as:

$$C = BC_{ar} - (C'_{sl} + C'_{lc} + C'_{fa}) \quad (31)$$

The volume of CO_2 in Nm^3/kg produced by burning C″ is:

$$V_{CO2} = \frac{22.4B}{12}\left(C_{ar} - \frac{80\%A_{ar}C_{sl}}{1-C_{sl}} - \frac{15\%A_{ar}C_{lc}}{1-C_{lc}} - \frac{5\%A_{ar}C_{fa}}{1-C_{fa}}\right) \quad (32)$$

with 22.4 Nm^3 CO_2/mol, and 12 kg carbon/mol.

3. Data collection

Data of sample boilers were obtained from thermal-balance tests conducted by specialized teams in Liaoning province, north of China, from October 2016 to March 2017. Several factors will influence the accuracy of the test, such as the location of the measuring point, the variation of the heat load and condition as well as the instrument error. The selection of samples was based on the well-functioning industrial boiler system election project implemented by the provincial government. In this study, 141 certificates for boilers were collected from the project. As a result of that the capacity (Q) and the operation condition of sample boilers were slightly better than the local average level.

Among the sample boilers, the medium size boilers 7 MW (10 t/h), 14 MW (20 t/h), and 21 MW (30 t/h) accounted for 22%, 18%, and 21% of the total boilers, respectively. Only a few boilers under 5 MW and more than 100 MW were tested. The average capacity of the 141 boilers was 31.83 MW. The output medium of the 141 boilers was divided into two types: hot water for 60% of the boilers representing a total capacity of 3379 MW and saturated steam for 40%, of the boilers with a total capacity of 1657 t/h. The histogram of boilers capacity is illustrated in Fig. 3. The capacity units of all boilers were converted into MW (1 t/h ≈ 0.7 MW).

The equipment for coal-fired boilers in Liaoning province, as shown in Fig. 4, is dominated by the traveling grate stoker accounting for 92.39% of the boilers and further includes chain-stoker (46.66%), reciprocating stoker (24.92%), and fixed stoker (20.81%).

In this study, the sample boilers were all traveling grate stoker with chain-stoker comprising 73.04% and reciprocating stoker accounting for 26.96%, of the boilers, respectively.

The coal for industrial boilers was divided into two categories: bituminous coal and brown coal. The heat value of bituminous coal is higher and the ash content is lower than brown coal. The component data for coals are available in the current standard and were obtained by assaying in a laboratory as shown in Table 1.

The thermodynamic measuring points and instruments are shown in Fig. 5 and Table 2.

4. Results

In this section, the results of thermal test data, energy analysis, exergy analysis, and CO_2 emission analysis of sample boilers have been provided.

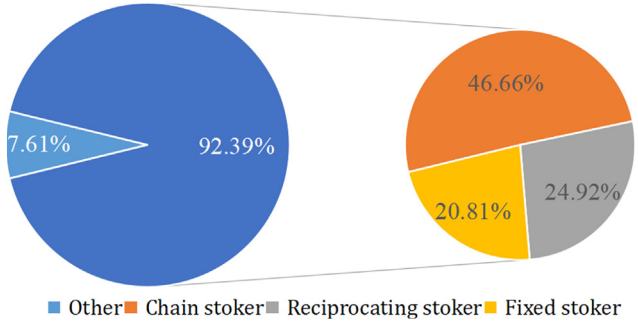


Fig. 4. Equipment for coal-fired boilers in Liaoning province.

Table 1
Data on coal components in Liaoning province.

	Bituminous coal (recommended)	Bituminous coal (average)	Brown coal (recommended)	Brown coal (average)
M_{ar}, %	5–10	15.41	> 20	32.70
A_{ar}, %	< 25	27.65	< 30	34.13
V_{ar}, %	> 20	23.85	> 40	28.62
S_{ar}, %	< 0.8	0.73	< 2.0	2.21
LHV, kJ/kg	15,500–19,700	16,693	8400–15,000	11,150

4.1. Analysis of thermal test data

Based on the methods described in Section 2.1, the average thermal efficiency of 141 sample boilers was estimated to be 76.08%. The highest efficiency was 87.90%, while the minimum efficiency was estimated at 62.28%. Apart from these samples, according to the efficiency range, the boilers could be divided into three groups:

(1) Boilers in the mediocre efficiency level (75–80%) taking up 34% in quantity, 30% in capacity;
(2) Boilers with some energy saving potential (η < 75%) making up 29% in quantity, 20% in capacity;
(3) Boilers with favorable operation conditions (η > 80%) accounting for 37% in quantity, 50% in capacity.

The data for thermal efficiency are illustrated in Fig. 6.

According the energy analysis model proposed in Section 2.1, the energy loss of a coal-fired industrial boiler in its daily operation is divided into five streams. The average specific values of the five energy

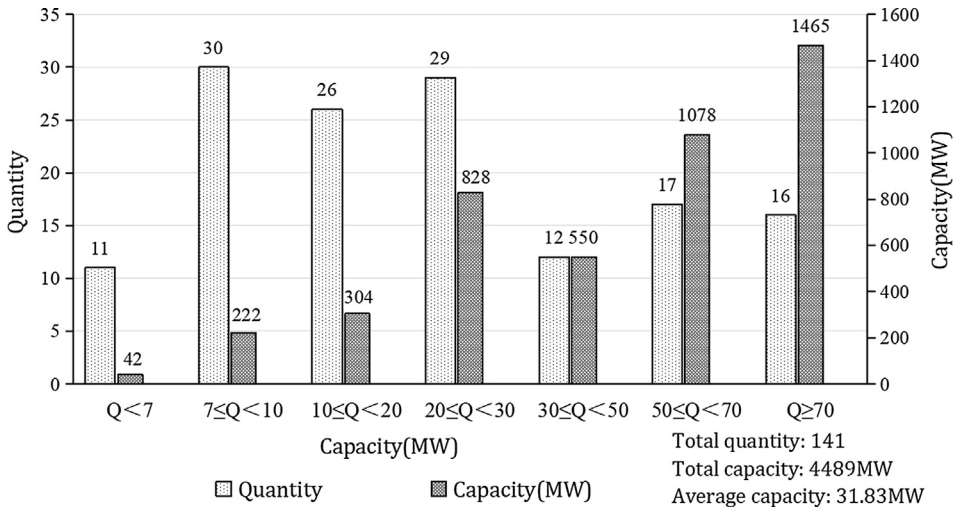


Fig. 3. Histogram of boiler capacities.

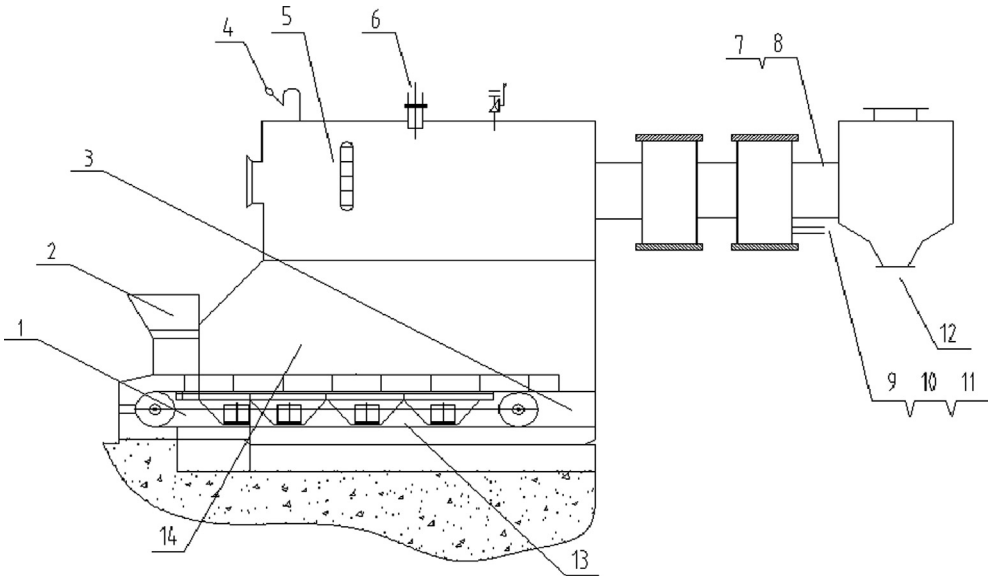


Fig. 5. Diagram of the thermodynamic measuring points.

losses are presented in Fig. 7.

As can be seen from Fig. 7, Q2 and Q4 are the leading energy losses among the five streams.

The indicators of test data affecting the thermal efficiency of industrial boilers mainly consisted of the following: flue gas temperature, excess air ratio α, CO content of flue gas, carbon content in slag, leakage coal, and fly ash. Table 3 shows the statistical average data for the boiler tests carried out in the project.

4.2. Energy analysis

In this study, several typical samples were selected to explain the heat loss in a coal-fired industrial boiler in detail. The typical samples covered a variety of capacities and various types of heat losses, in order to illustrate the effect of different factors on boiler thermal efficiency. All the test data derived from the parameters of boilers in steady daily operation state are shown in Table 4.

The sample boilers reflected several problems typical of the operation of industrial boilers including excess air ratio, flue gas temperature, and unburned carbon content of the cinder. Additionally, a sample boiler in an optimal condition was used as a benchmark.

The energy streams of the first sample boiler $1^{\#}$ DZW7.0-1.0-AII are shown in Fig. 8. Energy streams of other sample boilers can be found in the Supplementary material.

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.applthermaleng.2018.08.069.

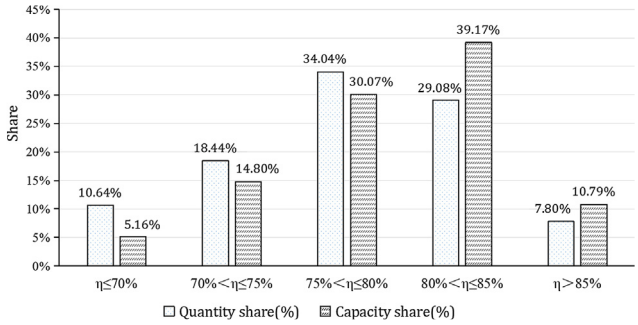


Fig. 6. Histogram of boiler efficiencies.

Several observations could be made from the thermal test and energy analysis of sample boilers:

(1) The energy loss of coal-fired industrial boilers was mainly caused by two items: Q_2 and Q_4 due to unburnt carbon, both of which account for about 10% of the losses.
(2) The main factors affecting Q_2 included flue gas temperature and excess air ratio at the last heating surface.
(3) The factors that affect Q_4 included the content of unburnt carbon in

Table 2
Instruments for thermodynamic measurements.

No.	Measuring item	Measuring point location	Instrument
1	Leakage coal sampling and weighing	Under the stoker	Electronic scale
2	Coal sampling and weighing	Coal scuttle	
3	Slag sampling and weighing	End of the stoker	
4	Hot water (steam) pressure	Boiler drum	Pressure gauge
5	Flow rate of hot water (steam)	Output main tube	Electronic scale
6	Feed water sampling	Input main tube	
7	Flue gas analysis	The last heating surface	Flue gas analyzer
8	Flue gas temperature		Platinum resistance thermometer
9	Feed water temperature	The feed water tube into economizer	
10	Feed water pressure		
11	Flow rate of feed water		Turbine flowmeter
12	Fly ash sampling and weighing	Dust collector	Collecting bottle
13	Combustion air temperature	Air supply tube	Platinum resistance thermometer
14	Surface temperature	Boiler surface	Infrared radiation thermometers

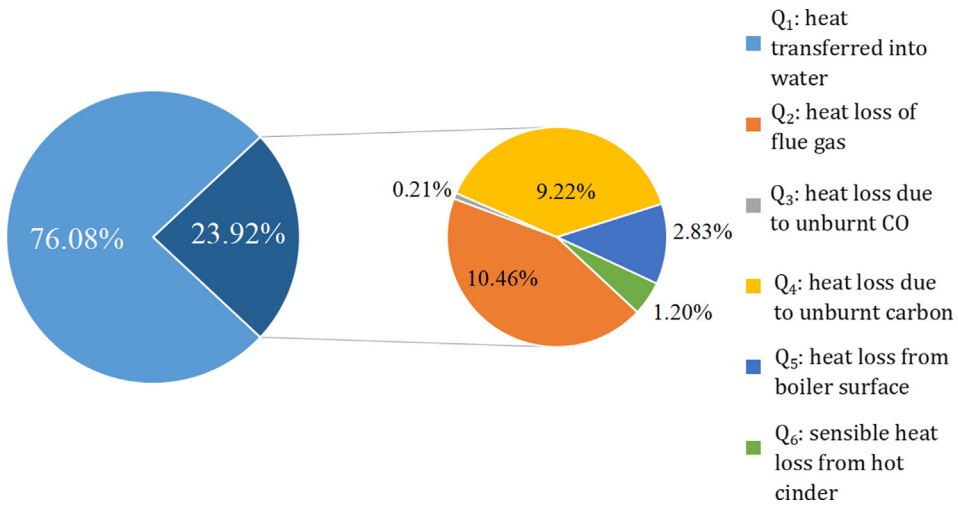


Fig. 7. Average values of the five energy losses for the of sample boilers.

Table 3
Average values of key indicators of boiler efficiency.

Capacity, MW	T_{fg}, °C	α	CO, ppm	C_{sl}, %	C_{lc}, %	C_{fa}, %	η, %
Q < 7	147.20	3.01	52.82	12.27	22.55	29.33	72.86
7 ≤ Q < 10	148.16	2.27	27.50	13.94	33.94	26.65	74.81
10 ≤ Q < 20	152.73	2.47	56.00	12.77	26.04	24.58	75.83
20 ≤ Q < 30	154.55	2.29	39.08	12.01	27.20	24.75	75.13
30 ≤ Q < 50	144.36	2.33	38.96	10.45	24.86	23.44	77.05
50 ≤ Q < 70	160.21	1.71	48.60	10.72	24.18	26.99	81.27
Q > 70	141.44	1.62	22.71	12.35	19.21	21.69	81.60
Average	150.84	2.24	39.50	12.04	25.39	24.99	76.08

cinder, lower heating value of coal, and the ash content of coal.

(4) Q_3 takes a slight portion on account of heat loss in coal-fired industrial boilers and lead to the result that Q_3 assumed to be set at 0.2% for the boilers with CO content in flue gas lower than 500 ppm.

(5) The main factors influencing Q_5 and Q_6 were the temperatures of boiler surface and hot cinder, respectively. The default temperature of hot cinder for stoker fired boiler was 600 °C. For boilers with different capacities, the Q_5 heat losses are presented in Table 5 as follow:

It should be noted that the values in Table 5 are enforceable in boilers with a load of 75% and more. Therefore, when the load is less than 75%, the value of Q_5 needs to be fixed.

4.3. Exergy analysis

According to the method proposed in Section 2.2, compared to energy analysis, exergy analysis requires data obtained from detailed test of industrial boiler performance. Because of the distinct data requirement, the analyses of data for different boilers are presented in this section.

The exergy analysis results of typical samples as well as their comparison with results from the energy analysis are shown in Table 6. The basic information for the boilers can be found in the Supplementary material.

The exergy streams of the first sample boiler 1# SZW7.0-1.0-AII are shown in Fig. 9. Exergy streams of the other sample boilers can be found in the Supplementary material.

Table 4
Basic data and results of energy analysis for typical samples.

Items	1# DZW7.0–1.0-AII	2# SZL20-1.6-AII	3# DHL35-2.5/300-AII	4# SHL20-1.25-AII	5# SHW46-1.6/130/70-AII
Remark	C_{lz}	Excess air	T_{py}	Excess air,T_{py}, C_{lz}	Well-functioning
Medium	Hot water	Steam	Steam	Steam	Hot water
Capacity, MW	7	14	24.5	14	46
Coal consumption, t/a	2902	3653	12,195	9577	13,892
Load, %	75.71	42.01	77.71	61.55	70.56
LHV, kJ/kg	16,467	20,108	18,890	12,310	17,623
Ash content of coal, %	21.23%	21.70	27.10	29.80	13.27
Excess air ratio, lada	2.14	3.48	2.00	3.39	1.79
Flue gases temperature, °C	147	153	201	181	133
CO content of flue gases, ppm	100	100	100	100	100
C_{sl}, %	37.21	10.50	9.80	15.23	9.94
C_{lc}, %	24.87	32.81	30.24	15.35	30.26
C_{fa}, %	24.87	24.92	13.90	26.82	21.16
Average temperature of surface, °C	69.26	63.23	80.74	75.62	62.56
Temperature of hot cinder, °C	600	600	600	600	600
Q_2 heat loss of flue gases,%	9.32	16.3	13.44	18.66	7.85
Q_3 heat loss due to unburned CO, %	0.20	0.20	0.20	0.20	0.20
Q_4 heat loss due to unburned carbon, %	15.96	5.96	6.24	10.6	3.72
Q_5 heat loss from boiler surface, %	1.70	2.90	2.90	2.11	1.95
Q_6 sensible heat loss from hot cinder, %	0.94	0.54	0.71	0.77	0.37
Efficiency, %	71.88	74.10	76.51	67.66	85.91

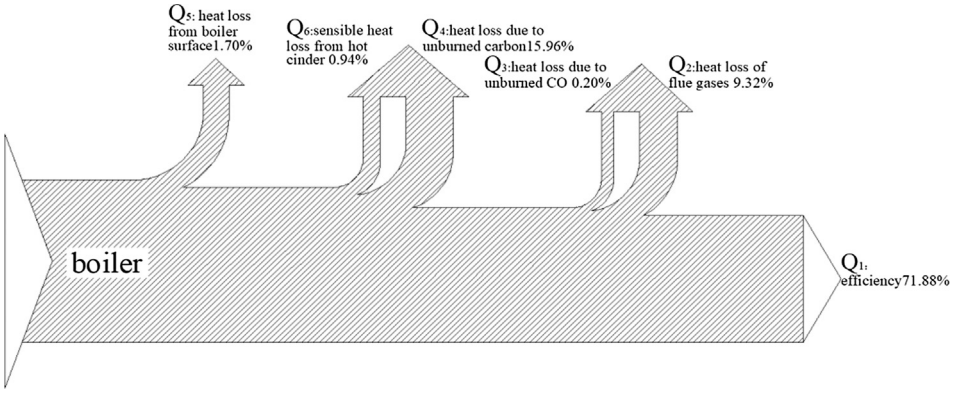

Q5: heat loss from boiler surface1.70%
Q6:sensible heat loss from hot cinder 0.94%
Q4:heat loss due to unburned carbon15.96%
Q3:heat loss due to unburned CO 0.20%
Q2:heat loss of flue gases 9.32%
boiler
Q1: efficiency71.88%

Fig. 8. Energy streams diagram of the 1# DZW7.0-1.0-AII typical boiler.

Table 5
Q5 heat loss under different boiler capacities.

Boiler capacity	t/h	≤4	6	10	15	20	35	≥65
	MW	≤2.8	4.2	7.0	10.5	14	29	≥46
Q_5	%	2.9	2.4	1.7	1.5	1.3	1.1	0.8

The following results were obtained from exergy analysis of sample boilers:

(1) Typical sample boilers functioned reasonably well. While the energy efficiencies were all above 80%, the exergy efficiencies were very low.
(2) The efficiency of the steam boiler was calculated to be 27.97%, which is much higher than that of hot water boiler. The average exergy efficiency of hot water boiler was only 12.88% and is attributed to the difference in the energy grade of output medium conducted by local heating strategies
(3) Contrary to the energy consumption, I_1 and I_2 are the dominant exergy streams, indicating exergy destruction induced by irreversibility in coal combustion and heat transfer process of coal-fired industrial boilers.

4.4. CO_2 emission analysis

The following results were obtained by calculations based on the methods introduced in Section 2.3 In order to calculate the CO_2 emissions of boilers, the following assumptions were made: the annual operating time of a boiler was 150 days at a daily run time of 12 h.

To elucidate the CO_2 emissions of 141 sample boilers under normal working conditions, a histogram has been developed (Fig. 10).

The minimum CO_2 emission among the 141 samples was found to be 101.55 kg-CO_2/GJ, the maximum was 246.74 kg-CO_2/GJ, and the average value was 147.13 kg-CO_2/GJ.

The majority of samples were within the range of 120 kg-CO_2/GJ to 160 kg-CO_2/GJ, the proportion of which is 69.51% for quantity, and 71.16% for capacity.

5. Discussion

In this section, the results from this study are compared to other research in order to assess the limitations of the industrial boiler operation. Subsequently, the energy saving potential and corresponding suggestions for coal-fired industrial boilers in China are presented.

5.1. Comparison with other studies

Presently, only a few studies have been conducted on exergy and energy analysis of industrial boilers. The comparison of results from this study with previous research is shown in Table 7. The oil-fired boiler and gas-fired boiler are used for heating in the world. Due to the difference in energy structure and heating strategy, the coal-fired industry boilers have been applied widely in the current district heat in China. Very few published papers and reports performed energy and exergy analysis on the coal-fired boiler in the open literature. In Ref. [11], an energy efficiency analysis had been performed based on the data of 200 sample boilers. However, the operation and efficiency of the industry boiler have changed with the improvement of component and management in the last decades. The results in this study are obtained from in-use boilers, which are more representative and evaluate the performance of industry boiler more clearly.

The exergy efficiencies of sample boilers in this study are lower than those in others, largely due to the current local heating strategy being limited by the capacity of auxiliary equipment in the district heating boiler system. For production safety, most hot water boilers were found to run under unsuitable conditions with the medium outputting at a lower temperature and pressure in comparison to the rated level. In order to remedy the insufficient parameters of the medium, it is necessary to ensure the total heating quantity as well as a larger flow supply. Consequently, the energy grade of output medium is not only inferior but is detrimental to exergy utilization in the boiler system.

In the past decade, the average boiler energy efficiency of coal-fired industrial boilers in China has been ~65% while the CO_2 emission level has been 0.14–0.20 Nm^3-CO_2/kg-steam and 110–157 kg-CO_2/GJ.

It can be inferred that the coal-fired industrial boiler in China has been improved at the operation and equipment level, however, a gap

Table 6
Exergy analysis results of typical samples.

		1# SZW7.0-1.0-AII	2# DZL10-1.25-AII	3# DZL29-1.0-AII	4# QXL70-1.6-AII
Loss of flue gas, %	Energy	7.43	8.26	7.72	4.23
	Exergy	1.95	1.85	1.74	0.66
Loss due to unburnt cinder, %	Energy	8.47	5.07	3.64	8.59
	Exergy	0.42	0.34	0.06	0.06
Loss from boiler surface, %	Energy	1.70	2.31	1.56	1.02
	Exergy	0.93	1.03	0.99	1.15
Loss of cinder heat, %	Energy	0.99	0.36	0.92	0.67
	Exergy	0.14	0.15	0.11	0.09
Efficiency, %	Energy	81.21	83.79	85.96	85.29
	Exergy	14.40	27.97	10.83	13.41
Exergy destruction of combustion, %		40.14	35.62	38.11	30.96
Exergy destruction of heat transfer, %		42.01	33.40	49.16	55.10

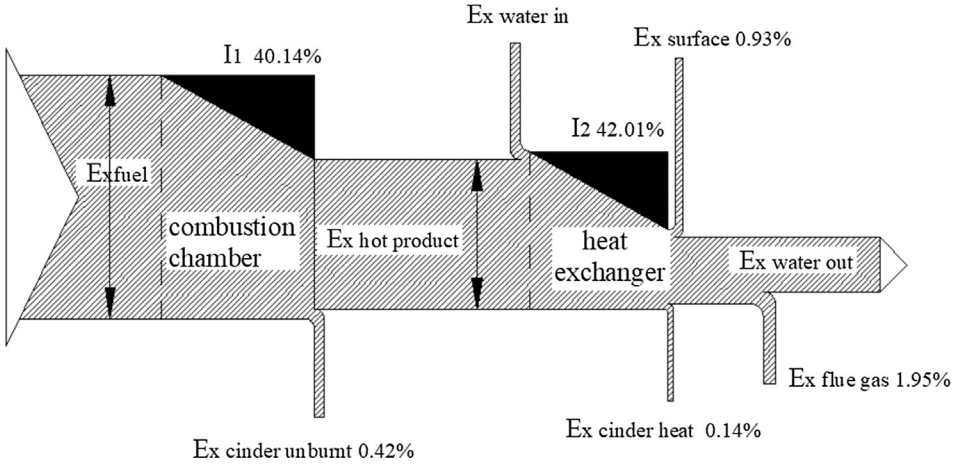


Fig. 9. Exergy streams diagram of the 1# SZW7.0-1.0-AII typical boiler.

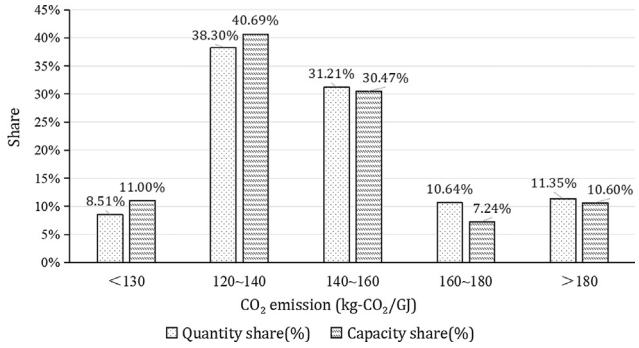


Fig. 10. Histogram of CO_2 emission of 141 sample boilers.

exists when compared to standards maintained in some other countries. Meanwhile, the control of CO_2 emissions has not improved significantly.

5.2. Energy promotion of a boiler

In this section, the impact of several factors on thermal efficiency will be discussed under the framework of combustion and heat transfer.

5.2.1. Flue gas

(1) Flue gas temperature:

Recovering a part of the heat energy from the flue gas can improve the efficiency of the boiler. The test results and scatter diagram of energy efficiency and flue gas temperature are shown in Figs. 11 and 12.

Flue gas temperature is the one of main reasons for high Q_2 heat loss. For every 10 °C increase in the temperature, in general, the Q_2 heat loss increases by 1%. For most sample boilers, the operational condition of low flue gas temperature (< 125 °C) is unfavorable for heat transfer in the boilers. The SO_2 in the flue gas liquefies when the temperature is below the dew point. Thus, at the low temperature, acid corrosion of the metal heating surface impacts the heat exchange to reduce the overall thermal efficiency of the boiler. The relationship of flue gas temperature and acid dew point for different S contents of coal and excess air is shown in Fig. 13.

Among the 141 sample boilers, 62% performed well in controlling the heat loss of flue gas (Q_2 < 10%) and 12% performed poorly (Q_2 > 15%). The remaining 12% showed energy saving potential (10–15%).

(2) Excess air factor

Excess air factor, an important parameter for the boiler's daily operation, is equal to the ratio of actual air coefficient to theoretical air coefficient. It has a huge influence on the burning condition and the emission of fuel gases. A more reasonable excess air factor can improve the operation level of the boiler. Figs. 14 and 15 present the test results of energy efficiency and excess air factor.

As the excess air factor increased by 0.1%, the oxygen content of fuel gas increased by 1.9% and Q_2 increased by 3.8%.

In theory, the excess air factor should be close to 1.0 when the boiler is in stable operation. However, the supply of combustion air leaves a surplus due to emission resistance of the flue gas and the adjustment of the dynamic demand in real working conditions. The recommended excess air factor should be less than 1.5.

Only 16 boilers, which accounted for 11% of the 141 sample boilers, had a rational excess air factor. Of the remainder, 53 boilers, accounting for 38% of the boilers, had an excess air factor ranging between 1.5 and 2, while 51 boilers, accounting for 36%, showed values between 2 and 3. The excess air factor of the remaining 21 boilers, accounting for 15%, was above three.

5.2.2. Unburnt cinder

The carbon content of cinder is the main influence factor of Q_4. The

Table 7
Comparison of results from this study with other studies.

The capacity of boilers	Type of products	Type of fuels	Energy efficiency,%	Exergy efficiency,%	References
3 t/h	Steam	Coal	72.46	24.89	Saidur et al. [13]
–	Hot water	Natural gas	82.21	32.77	Terhan et al. [2]
–	–	–	80.8	75	Balkrishna (2009)
10 t/h	Steam	Coal	83.79	27.97	This study
7 MW	Hot water	Coal	81.21	14.40	
29 MW	Hot water	Coal	85.96	10.83	
70 MW	Hot water	Coal	85.29	13.41	

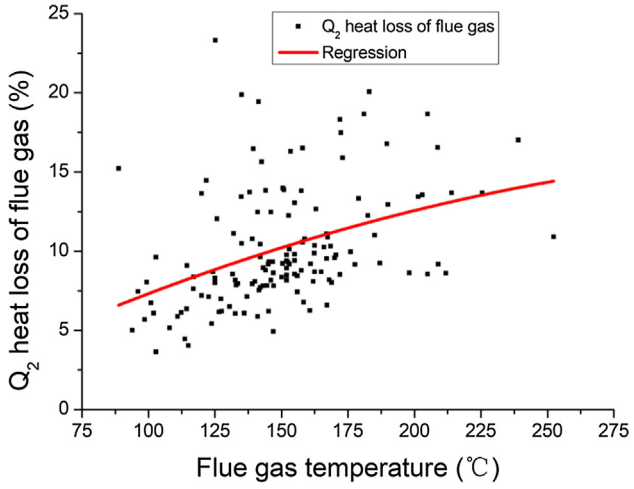


Fig. 11. Flue gas temperature vs Q_2 loss.

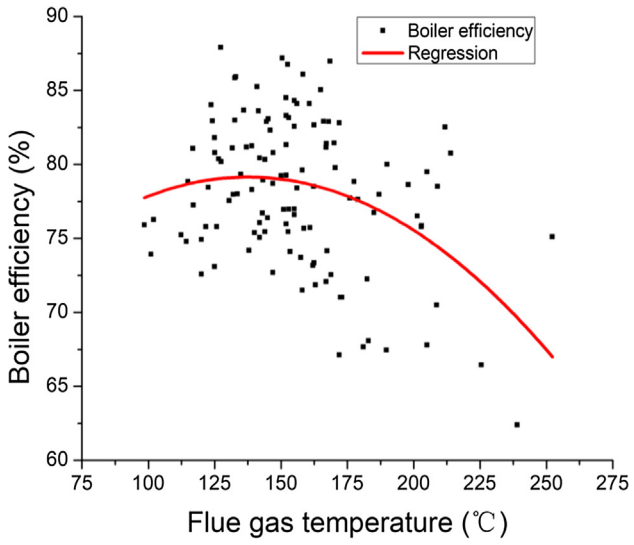


Fig. 12. Flue gas temperature vs boiler efficiency.

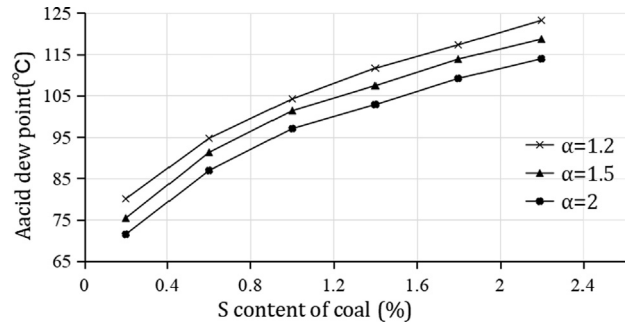


Fig. 13. Acid dew point for different S contents of coal and excess air.

proportion of slag, coal leakage, and fly ash in the solid exhaust was found to be 80%, 15%, and 5%, respectively. The following figure (Fig. 16) shows the influence of carbon content of slag on boiler efficiency. The influence of coal leakage and fly ash can be found in the Supplementary material

The high carbon content is disadvantageous for Q_4 and the combustible content of slag was shown to have the greatest effect. The carbon content of slag is mainly affected by the corresponding operation parameters of the coal feeder, grate equipment, and the coal quality. An unsuitable combination of the three will cause an exorbitant

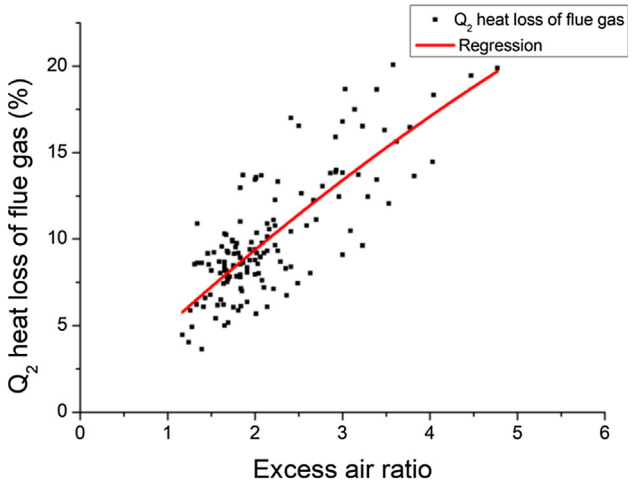


Fig. 14. Excess air factor vs Q_2 loss.

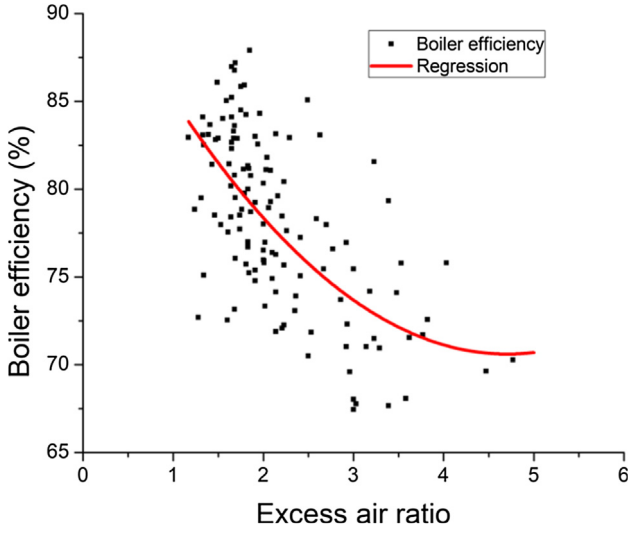


Fig. 15. Excess air factor vs boiler efficiency.

local temperature of the grate and an incomplete combustion of coal on the grate.

The Q_4 of the 141 sample boilers averaged 9.22%. The number of boilers with $Q_4 < 7.25\%$ was 52 which accounted for 37% of the total

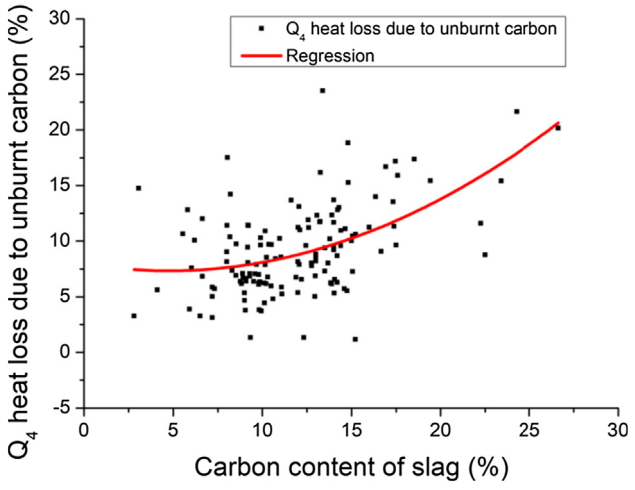


Fig. 16. Carbon content of slag vs Q_4 loss.

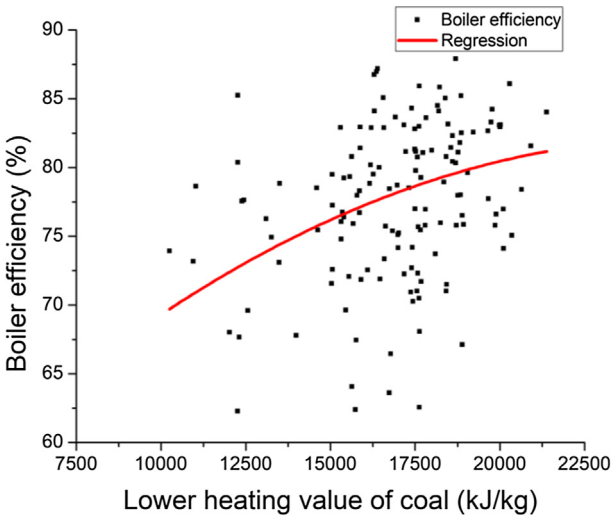


Fig. 17. Heating value of coal vs boiler efficiency.

boilers. Sixty-three boilers, accounting for 45% of total boilers, showed values between 7.25% and 12.25%. The remaining 26 boilers showed $Q_4 > 12.25\%$ and accounted for 18% of the total boilers.

5.2.3. Daily operation

A coal-fired boiler is a complex industrial system. Besides the Q_2 and Q_4 heat losses, there are several factors affecting the overall operation efficiency of the coal-fired boiler.

Compared to coal used for boilers in power plants, the quality of coal used in industrial boilers is poor with high ash, lower heating value, and sulfur content. The relationships of efficiency and the quality of coal are illustrated in Figs. 17 and 18.

Moreover, the operating load of sample boilers is very different, and boilers generally operate at low load condition. In Figs. 19 and 20, the impact of per-unit installed capacity and load on efficiency is shown:

The quality of coal has an impact on the boiler operation: boilers using high heat value coal are generally more efficient, moreover, the influence of ash content of coal is more remarkable; as the ash content increases, the efficiency of the boiler lowers.

High capacity boilers tend to be more efficient during the actual operation. The larger the boiler capacity, correspondingly larger the grate area, and subsequently, the arrangement of heating surface is relatively reasonable. The waste heat recovery equipment for flue gas

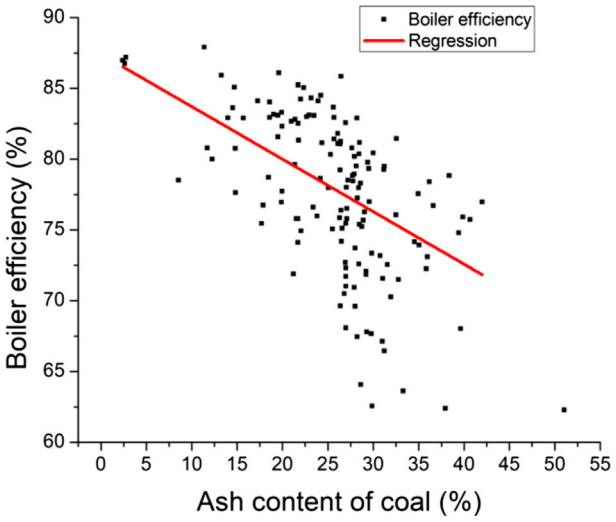


Fig. 18. Ash content of coal vs boiler efficiency.

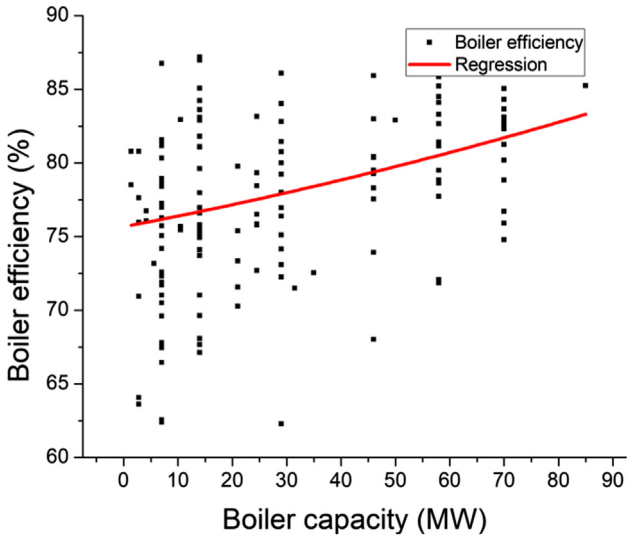


Fig. 19. Boiler capacity vs boiler efficiency.

such as economizer and the air preheater are also equipped with higher rate. Therefore, as long as they operate at reasonable load, the efficiency of combustion and heat transfer is advantageous when compared to small boilers. As shown in Fig. 20, when the load is between 70% and 100%, the boilers performance improves.

5.3. Coal saving and pollution reducing by energy efficiency promotion

The results of the thermal test and energy analysis were compared with the specified limits of the current standards.

For different coal-fired industrial boilers, the corresponding thermal efficiency required for the standard is presented in Fig. 21. A division of 141 sample boilers according to different capacities is presented below:

$Q \leq 10$ MW: A total of 38 boilers, the average thermal efficiency of 73.92%, the thermal efficiency target value inducted in the standard was 84%, the limited value was 78%, only 11 samples met the requirements with a standard rate of 28.95%.
$10\ \text{MW} < Q \leq 20$ MW: A total of 33 boilers, the average thermal efficiency of 77.51%, the thermal efficiency target value inducted in the standard was 85%, the limited value was 79%, 14 samples met the requirements with a standard rate of 42.42%.
$Q > 20$ MW: A total of 70 boilers, the average thermal efficiency of 78.04%, the thermal efficiency target value inducted in the standard

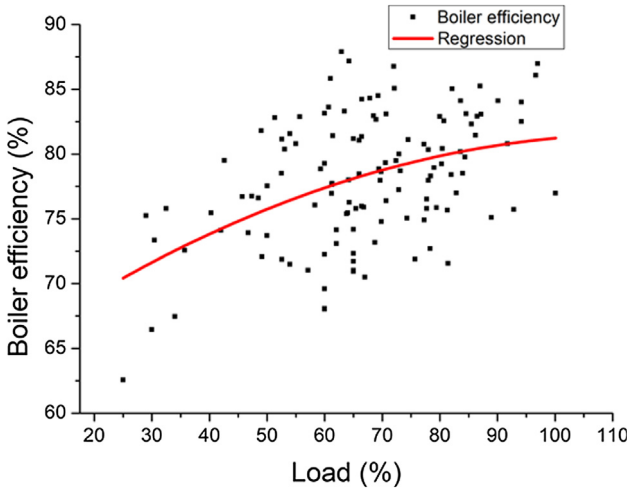


Fig. 20. Load vs boiler efficiency.

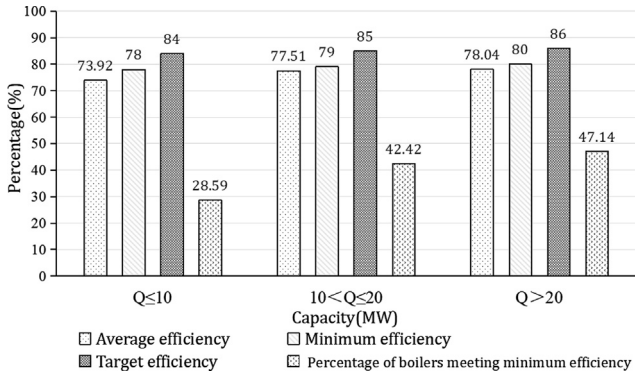


Fig. 21. Histogram of the efficiency status.

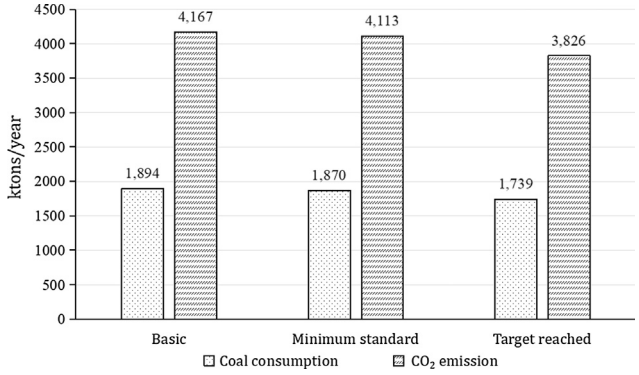


Fig. 22. Histogram of coal saving and CO_2 emission potential.

was 86%, the limited value was 80%, 33 samples met the requirements with a standard rate of 47.14%.

Taking the current test results as the basic scenario, assuming that the thermal efficiency of all the boilers in the future is up to standard, the economic benefits and environmental benefits of energy efficiency improvement were calculated and analyzed. Figs. 22 and 23. contains the energy conservation and emission reduction potential of 141 sample boilers.

It can be concluded from the diagram that in the basic scenario, the total annual coal consumption of 141 sample boilers is 1894 kt/yr and they produce 4167 kt CO_2, 45.45 kt SO_2, and 42.61 kt NO_x.

If the energy efficiency reaches standard level limits, it can reduce the coal consumption and CO_2 emissions by 24 kt/yr and 54 kt/yr, respectively. Correspondingly, the annual emissions of SO_2 and NO_x will be reduced by 0.58 kt and 0.54 kt, respectively.

Furthermore, if the boiler efficiency reaches the target level, the annual coal consumption will be reduced by 155 kt compared to the basic scenario and lead to the annual pollutant emission potential of 341 kt, 3.72 kt, and 3.48 kt for CO_2, SO_2, and NO_x, respectively.

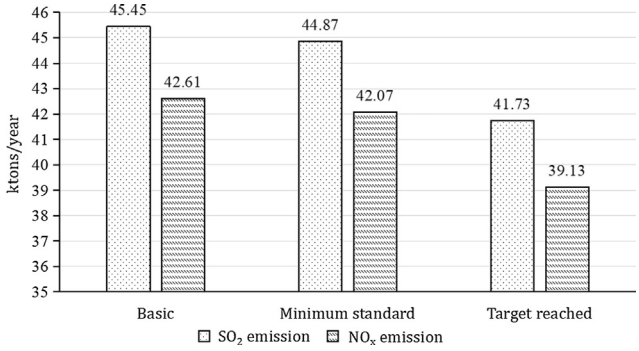


Fig. 23. Histogram of SO_2 and NOx emission potential.

6. Conclusions

The energy analysis based on the thermal tests shows that the average thermal efficiency of 141 coal-fired industrial boilers in Liaoning province of China is 76.08% several limitations are yet to be overcome and energy efficiency improved compared to the previous decade. The main energy losses were due to the heat loss of flue gas and unburnt carbon, both of which account for about 10% of energy loss. The indicators affecting the thermal efficiency of industrial boilers mainly consist of the following: flue gas temperature, excess air ratio, and carbon content in the cinder. Moreover, the quality of coal, boiler capacity, and load also influence the efficiency to a certain degree. The average energy efficiency and CO_2 emission of 141 boilers were estimated as 76.08% and 147.13 kg-CO_2/GJ, respectively.

An applicable exergy analysis model for coal-fired industrial was also proposed in this study. The exergy efficiencies of some typical boilers were calculated using this method. Exergy efficiency of the steam boiler was calculated as 27.97%, while that of a hot water boiler was found to be only about 12.88%. This difference can be attributed to the difference in energy grade of the output medium followed by the current heating strategy and limitations of the auxiliary equipment. Therefore, to improve the exergy utilization of coal-fired boilers, the limitations of the boiler auxiliary equipment needs to be addressed. Exergy loss was dominated by destruction due to the irreversibility in coal combustion and heat transfer, which accounted for 38% and 30% of the losses, respectively.

The standard rate of 141 boilers was calculated as 28.59%, 42.42%, and 47.14% for boiler capacities of $Q \leq 10$ MW, 10 MW $< Q \leq 20$ MW, and $Q > 20$ MW, respectively. At present, the potential for energy saving and emission reduction of coal-fired boilers is significant. Raising the efficiencies of 141 boilers to the target level proposed in the standard will lead to a decrease of coal consumption by 155 kt, emission reduction of 341 kt for CO_2, 3.72 kt for SO_2, and 3.48 kt for NO_x per year.

Acknowledgement

This work was supported by the National Key Research and Development Program (Project No. 2016YFB0601301, 2016YFB0601305). The authors gratefully acknowledge the reviewers and editors for their fruitful comments.

References

[1] International Energy Agency, World Energy Outlook 2017, 2017.
[2] M. Terhan, K. Comakli, Energy and exergy analyses of natural gas-fired boilers in a district heating system, Appl Therm Eng 121 (2017) 380–387.
[3] Ming Yang, Robert K. Dixon, Investing in efficient industrial boiler systems in China and Vietnam, Energy Policy 40 (2012) 432–437.
[4] International Energy Agency, World Energy Investment Outlook, 2014.
[5] H. Chen, J.N. Kang, H. Liao, et al., Costs and potentials of energy conservation in China's coal-fired power industry: a bottom-up approach considering price uncertainties, Energy Policy 104 (2017) 23–32.
[6] General Administration of Quality Supervision, Inspection and Quarantine of P.R.C. Bulletin on safety status of special equipment in China in 2016, 2017 (April 17, Chinese text), < http://www.aqsiq.gov.cn/zjsj/tjsj/tjsj14/ > .
[7] Ministry of Industry and Information Technology (MIIT), Seven governmental agencies jointly releasing the comprehensive implementation plan of improving coal-fired boiler energy-saving and environmental protection performance, 2014 (October 29, Chinese text), < http://www.miit.gov.cn/n1146290/n4388791/c4216991/content.html > (accessed 19 September 2016).
[8] Energy Research Institute of China (ERI), Roadmap Study on Achieving Technical Energy Conservation Potential in China's Industrial Sector by 2020, China Scientific Technology Press, Beijing, 2013.
[9] S. Dechert, China coal consumption & CO2 emissions drop in 2014, 2015, < http://cleantechnica.com/2015/03/13/china-coal-consumption-CO2-emissions-drop-2014/ > (accessed 19 September 2016).

[10] B. Shen, Y. Han, L. Price, et al., Techno-economic evaluation of strategies for addressing energy and environmental challenges of industrial boilers in China, Energy 118 (2017) 526–533.
[11] T. Zeng, L. Yang, K.A. Oye, et al., Coal utilization in industrial boilers in China – a prospect for mitigating CO_2 emissions, Appl Energy 63 (1) (1999) 35–52.
[12] J.J. Gao, Research on China High Energy Consuming Equipment Operation Status and Energy Saving Solutions, the Final Report of the Research Project on China High Energy Consuming Equipment Operation Status and Energy Saving Solutions Commissioned by the Chinese Academy of Engineering, China Science Press, Beijing, China, 2013.
[13] R. Saidur, J.U. Ahamed, H.H. Masjuki, Energy, exergy and economic analysis of industrial boilers, Energy Policy 38 (5) (2010) 2188–2197.
[14] I.H. Aljundi, Energy and exergy analysis of a steam power plant in Jordan, Appl. Therm. Eng. 29 (2–3) (2009) 324–328.
[15] C. Uysal, H. Kurt, H.Y. Kwak, Exergetic and thermoeconomic analyses of a coal-fired power plant, Int. J. Therm. Sci. 117 (2017) 106–120.
[16] L. Pattanayak, S.K. Ayyagari, Use of energy and exergy analysis in coal fired boilers, Int. J. Multidiscip. Sci. Eng. 5 (2014) 17–23.
[17] A.H. Mosaffa, L.G. Farshi, C.A.I. Ferreira, et al., Advanced exergy analysis of an air conditioning system incorporating thermal energy storage, Energy 77 (2014) 945–952.
[18] G.D. Vučković, M.M. Stojiljković, M.V. Vukić, First and second level of exergy destruction splitting in advanced exergy analysis for an existing boiler, Energy Convers. Manage. 104 (104) (2015) 8–16.
[19] G. Tsatsaronis, T. Morosuk, Advanced exergetic analysis of a novel system for generating electricity and vaporizing liquefied natural gas, Energy 35 (2) (2010) 820–829.
[20] Y. Xue, H. Tian, J. Yan, et al., Temporal trends and spatial variation characteristics of primary air pollutants emissions from coal-fired industrial boilers in Beijing, China, Environm. Pollut. 213 (2016) 717.
[21] X. Zhao, Q. Cai, S. Zhang, et al., The substitution of wind power for coal-fired power to realize China's CO_2, emissions reduction targets in 2020 and 2030, Energy 120 (2016) 164–178.
[22] J. Fang, G. Li, K. Aunan, et al., A proposed industrial-boiler efficiency program in Shanxi: potential CO_2-mitigation, health benefits and associated costs, Appl. Energy 71 (4) (2002) 275–285.
[23] GB/T 10180-2003, Thermal performance test code for industrial boiler (in Chinese).
[24] TSG G0003-2010, Energy efficiency test and evaluation regulation for industrial boiler (in Chinese).
[25] V.S. Stepanov, Chemical energies and exergies of fuels, Energy 20 (3) (1995) 235–242.
[26] C. Coskun, Z. Oktay, N. Ilten, A new approach for simplifying the calculation of flue gas specific heat and specific exergy value depending on fuel composition, Energy 34 (11) (2009) 1898–1902.